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NUMERICAL SIMULATION OF SEMI-INFINITE TARGET PENETRATION BY CONTINUOUS AND SEGMENTED RODS

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FEBRUARY 1990

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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13. ABSTRACT *(Maximum 200 words)*

This report presents results of a numerical study of continuous and segmented rod impacts into semi-infinite steel targets at velocities of 1.5-4 km/s. Variations in segment spacing and number of segments comprising a segmented rod were considered in addition to striking velocity variations. It is found that below 2 km/s, there is no advantage (in terms of penetration) in using segmented rods over continuous rods. However, for striking velocities exceeding 2 km/s, segmented rods show improved penetration with proper adjustment of segment number and spacing.

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1. INTRODUCTION

Of late, there has been renewed interest in the performance of segmented long rod penetrators against a variety of armor systems. The potential benefits of segmented penetrators are based on the qualitative advantage of multiple impacts of well-aligned and well-separated penetrator segments when compared to that of a single equivalent penetrator. Eichelberger in 1956 suggested that the penetration performance of a metallic jet with perfectly aligned (Eichelberger 1956), spaced segments could be enhanced by as much as 40% over that of continuous jets. Analytical work by Frank (1985) and numerical simulations by Kucher (1982), de Rosset (1981), de Rosset and Kimsey (1986), Sedgwick et al. (1987) as well as experiments by Charters (1986), Raatschen et al. (1989), Kivity, et al. (1989), Herbette (1989), and others tend to confirm enhanced penetration by well-aligned, properly spaced segments in comparison to equivalent mass and equivalent diameter continuous rods.

Most experiments performed to date have been confined to specific cases with very limited variation of relevant parameters. Calculations have also focused on selected problems. A large number of parameters enter into the determination of penetration performance of segmented rods. A full parametric study remains to be performed.

This report deals with numerical simulation of the penetration of homogeneous, effectively semi-infinite, rolled homogeneous armor (RHA) targets by continuous and segmented tungsten alloy (90% tungsten, 7% nickel, 3% iron, 25% swaged) rods. Calculations were performed varying striking velocity (V_s = 1.5, 2, 3, 4 km/s), segment spacing (1D, 2D, 4D where D = segment diameter), and number of segments (1, 5, 10, 20). The calculations were performed with a local version of the 1978 release of the EPIC-2 code (Johnson 1978), modified to include eroding slide line logic (Kimsey and Zukas 1986). Selected results were verified with HULL code (Matuska and Osborn 1987) computations. Material properties for the tungsten alloy were taken from split-Hopkinson bar data reported by Nicholas (1980), the yield stress taken to be 14.3 kb and the ultimate stress 20 kb at an effective plastic strain of 0.14. The RHA was modeled as an elastic-perfectly plastic material with a flow stress of 8 kilobars.

Two levels of failure may be modeled with the version of EPIC used for these studies, based on user-specified levels of effective plastic strain. When the first level is met, tensile and shear stresses are not allowed to develop in the affected element. The net result is that the element

behaves much like a liquid in that it can support only hydrodynamic compression. When the second level of effective plastic strain is reached, all stresses and pressures are set to zero. Element quantities are no longer included in the simulation, as though total failure had occurred. When this option is invoked, mass and momentum continue to be conserved since the masses and velocities of failed elements are associated with their nodes, and these are tracked throughout the computation. Energy, however, is conserved only approximately since element internal energies are no longer computed. This is a minor concern, however, since this latter value of strain is set at high (150-250%) levels (for lack of better failure models) so that the elements "removed" from the calculation would, in reality, appear as ejecta in ballistic experiments.

2. COMPUTATIONAL RESULTS

Figures 1-2 summarize results of calculations showing the effects of the number of segments, segment spacing, and segment velocity on penetration performance. The data for these figures are given in Tables 1-2.

2.1 Effects of Spacing and Velocity. Figure 1 and Table 1 show penetration as a function of segment spacing and velocity for impact velocities to 2 km/s. The measure of penetration is the ratio P/L_o where P represents penetration depth (given in Table 1) and L_o the initial length of a continuous rod or the collapsed length of a segmented rod. The behavior of a segmented rod with five segments (each with L/D = 4 and segment spacing S varied between 1-4 projectile diameters, D,) is contrasted to that of a continuous rod of equivalent mass and diameter. It is clear that at ordnance velocities (striking velocities of 2 km/s or less) the penetration of segmented rods, as measured by P/L_o, falls below that of a continuous rod for small segment spacings, S/D, and approaches that of continuous rods as segment spacing is increased.

However, for striking velocities of 3 and 4 km/s, penetration by segmented rods, as measured by P/L_o, shows improvement over that of continuous rods as a function of both velocity and spacing (see Figure 2). For the situation studied here, gains of about 5% in P/L_o are achieved by going to segmentation at higher velocities. These gains can be further enhanced by 8-10% by appropriate adjustment of segment spacing. Representative computational results for a continuous rod at 4 km/s are shown in Figures 3-4. Figures 5-7 depict analogous results for an equal mass, equal diameter rod consisting of five segments with S/D =4.

The question naturally arises as to whether similar results hold for different segmentations. Figure 8 and Table 2 show (for segmented rods with spacing fixed at S/D =2) the same trends for projectiles with 20 segments (segment L/D = 1).

2.2 Effects of Segment Numbers. Calculations were also performed to study the effect of the number of segments on normalized penetration. Figure 8 and Table 2 summarize results for a continuous rod (1 segment) as well as rods consisting of 5 (segment L/D = 4), 10 (segment L/D = 2), and 20 (segment L/D = 1) segments striking semi-infinite RHA at velocities of 2, 3, and 4 km/s. Segment spacing was held at 2 diameters (S/D = 2). At 2 km/s, P/L_o is unchanged by varying the number of segments, within t.. .ccuracy of the numerical resolution employed in these studies. At the higher velocities, there is a modest gain. For example, for a 20-segment rod at 4 km/s, there is a 20% gain in P/L_o over that for a continuous rod, 12% for a 10-segment rod, and 6% for a 5-segment rod. For greater spacings, improvements on the order of 30% can be obtained. Recall, however, that these results are for the ideal case -- no initial yaw and segments perfectly aligned. In practice, such conditions are almost never realized, so that these can be considered as an upper limit on possible performance gains.

Typical deformations at various times after impact for a 20-segment rod at a striking velocity of 3 km/s are depicted in Figure 9.

2.3 P/L as a Penetration Performance Measure. It is the current custom to cast segmented penetrator results in terms of the nondimensional parameter P/L, with L being taken as the collapsed length of a segmented penetrator. It is always dangerous to depict situations involving a complex interaction of a number of variables in terms of a single parameter. That P/L is an imperfect measure of segmented penetrator performance can be seen in Figure 10 and Table 3, which merely recast the data in Table 2 using two normalization parameters - the collapsed length L_o and the extended length L. As Scheffler (1989) has pointed out, the latter is a more natural normalization factor. Many segmented rod configurations are launched with the presence of spacer materials which can affect penetration or are designed to extend in flight. To the degree to which such in-flight extensions are successful, they affect the spacing and, thus, the final penetration. Note from Figure 10 that conflicting conclusions can be drawn about the effectiveness of segmented penetrators depending on the normalization (collapsed or extended length) chosen. At minimum,

segmented rod information should be provided with raw data together with any normalizations deemed appropriate.

3. CONCLUSIONS

The simulations performed for this study indicate that, in terms of penetration performance:

a. There is no advantage to segmented rods over continuous rods at velocities below 2 km/s.

b. Segmented rods show improved penetration performance over continuous rods with proper adjustments of segment number and spacing for striking velocities exceeding 2 km/s.

c. The ratio of penetration to penetrator length is inadequate as a measure of performance for a complex impact situation influenced by a large number of parameters. To minimize confusion, raw data should be presented for segmented penetrator impacts. Otherwise, caveat emptor applies! As Scheffler (1989) has pointed out, and as is clear from Figure 10 and Table 3, the ratio of penetration to penetrator length may not be a good indicator of penetrator performance of segmented rods. Depending on the interpretation of length (collapsed or extended), conflicting conclusions can be drawn.

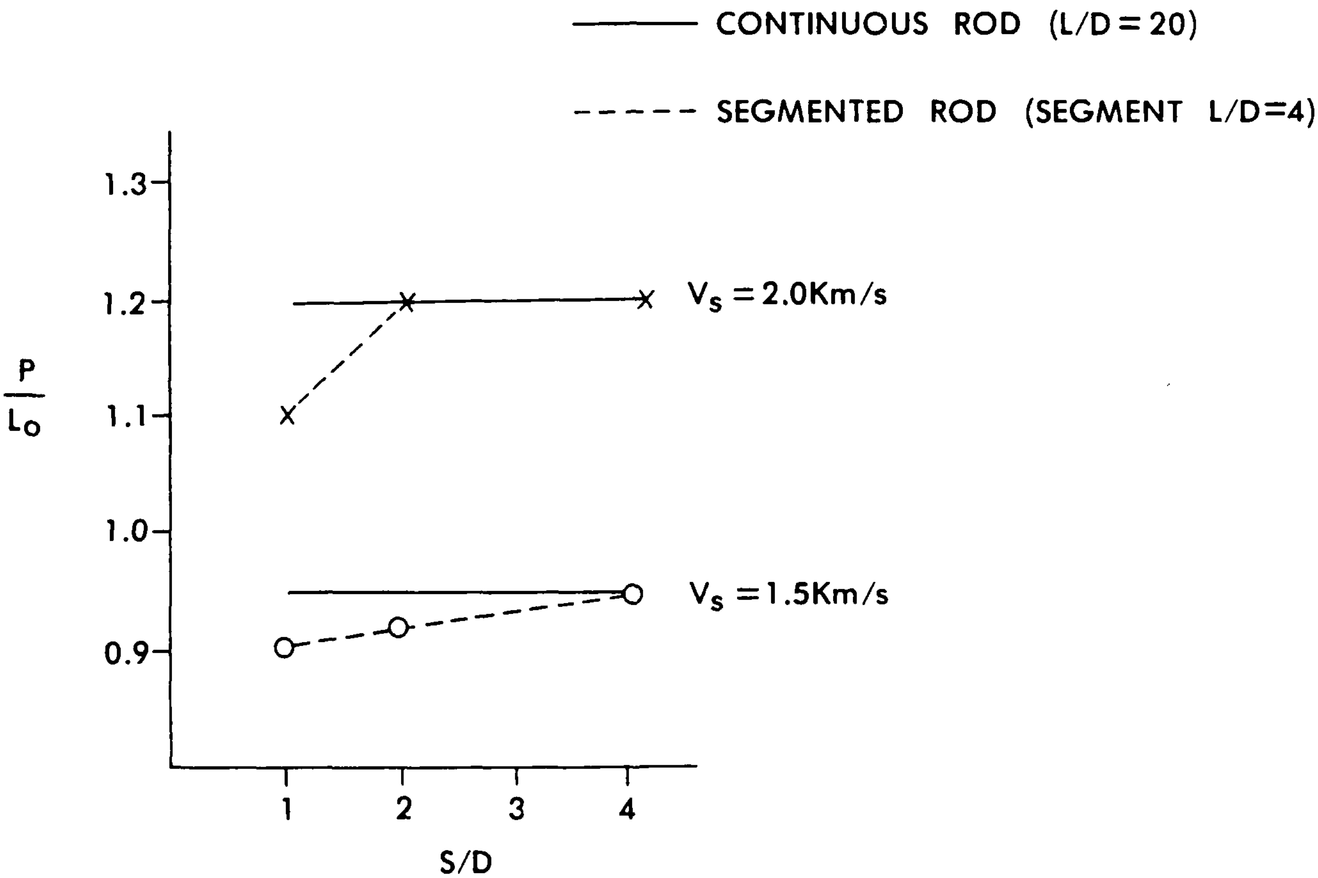

Figure 1. Comparison of Penetration Performance of Segmented and Equivalent/Mass-Equivalent Diameter Continuous Rods at Impact Velocities Below 2 km/s.

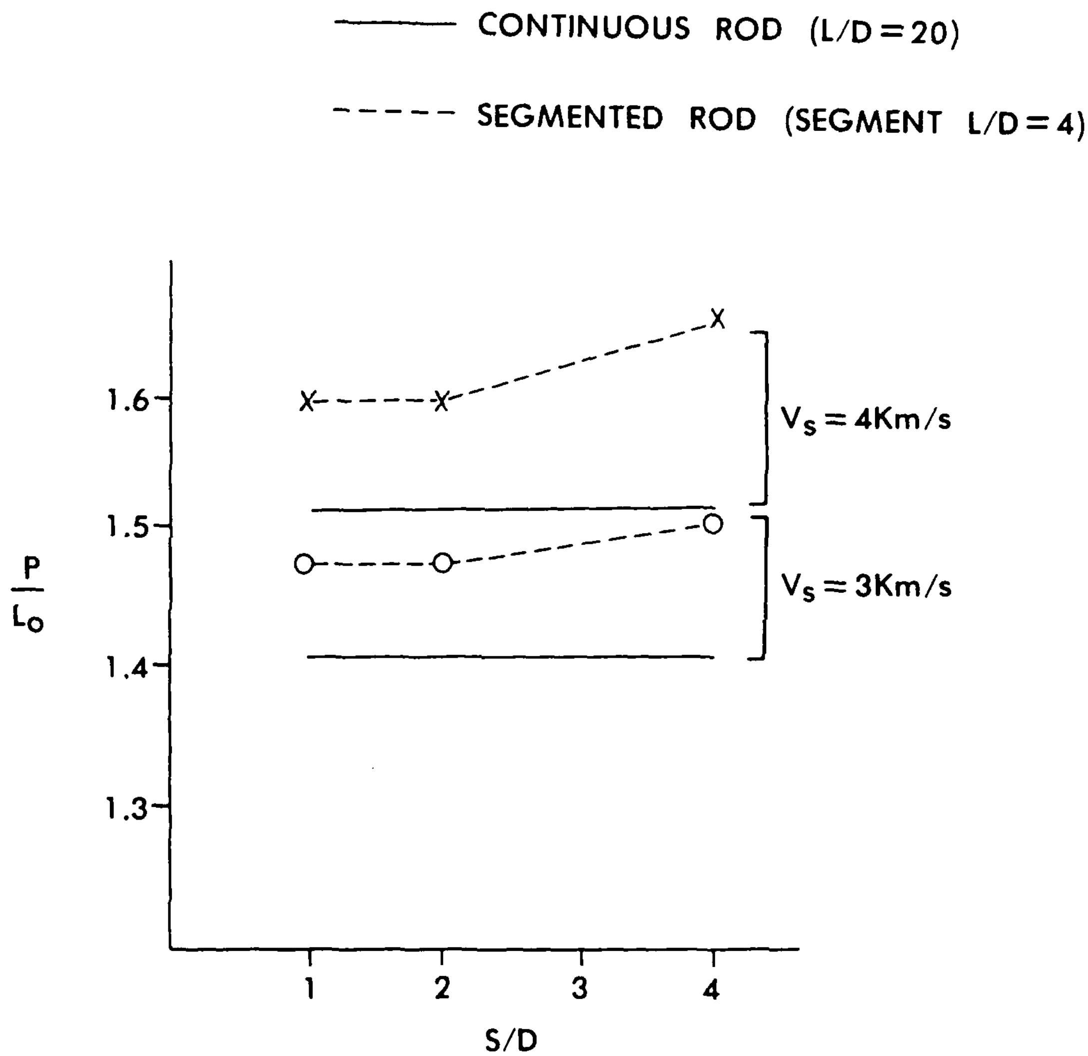

Figure 2. Comparison of Penetration Performance of Segmented and Equivalent/Mass-Equivalent Diameter Continuous Rods at Impact Velocities Above 2 km/s.

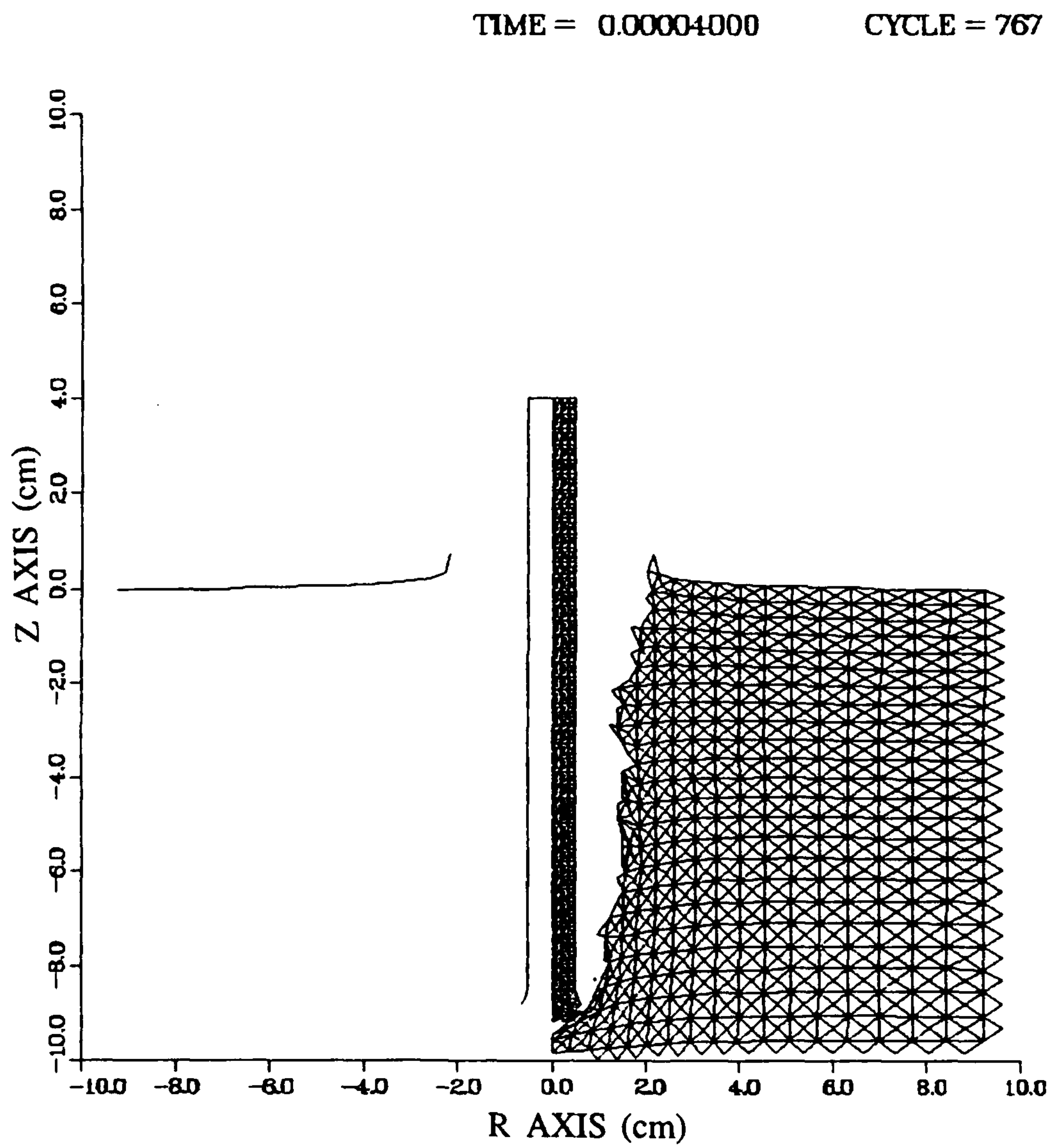

Figure 3. Computed Deformation of Continuous Rod and Target at 40 μs, V_s = 4 km/s.

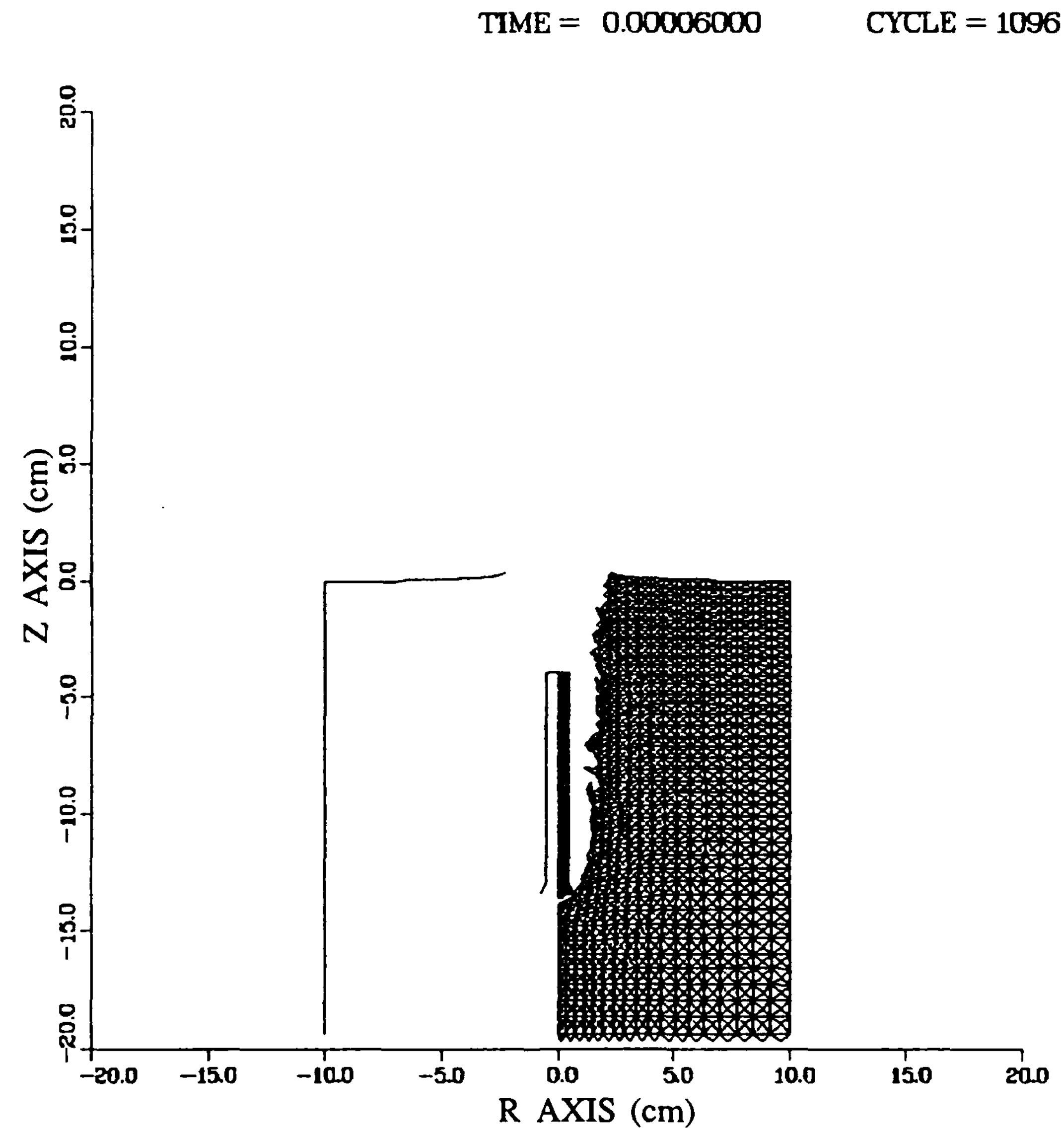

Figure 4. Computed Deformation of Continuous Rod and Target at 60 μs, V_s = 4 km/s.

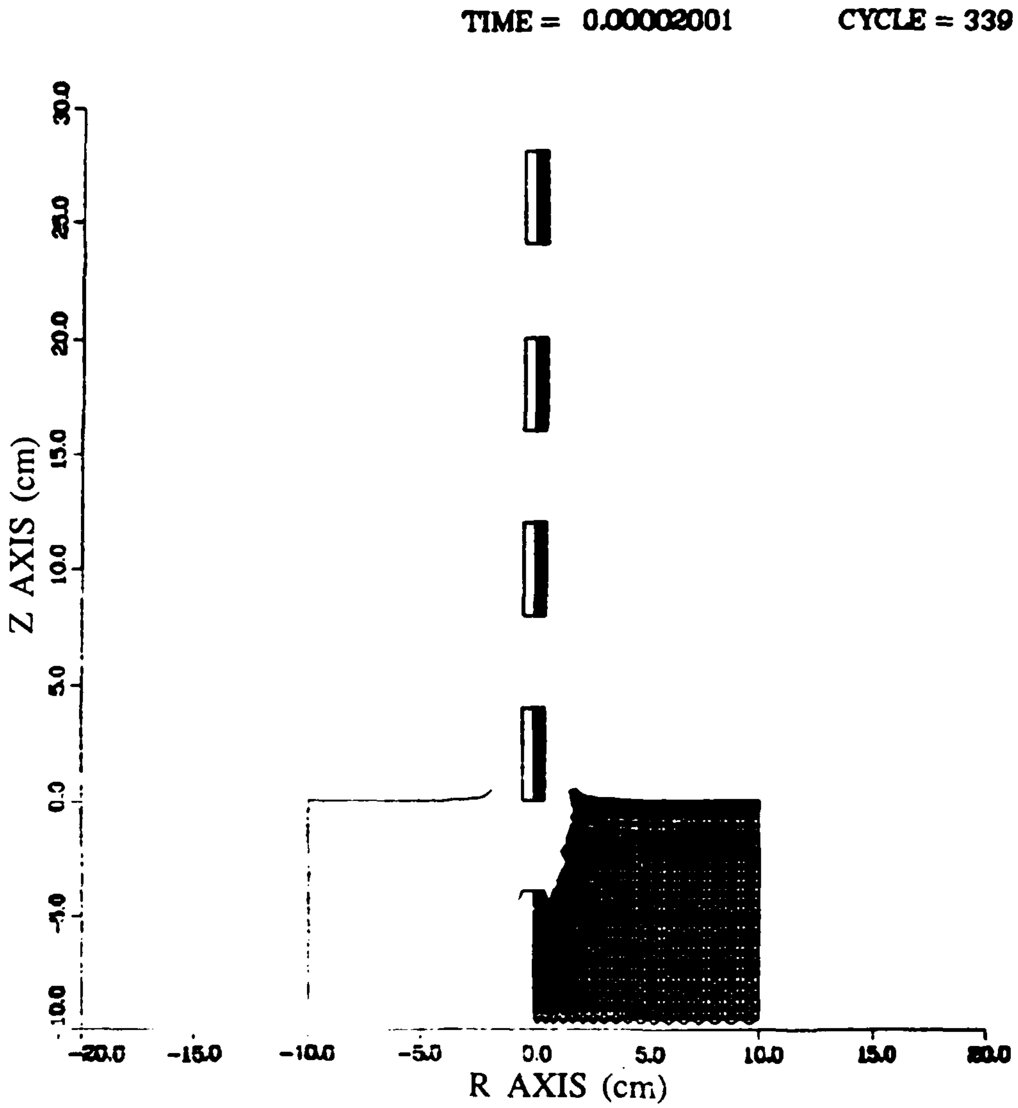

Figure 5. Computed Deformation of Segmented Rod and Target at 20 μs, V_s = 4 km/s.

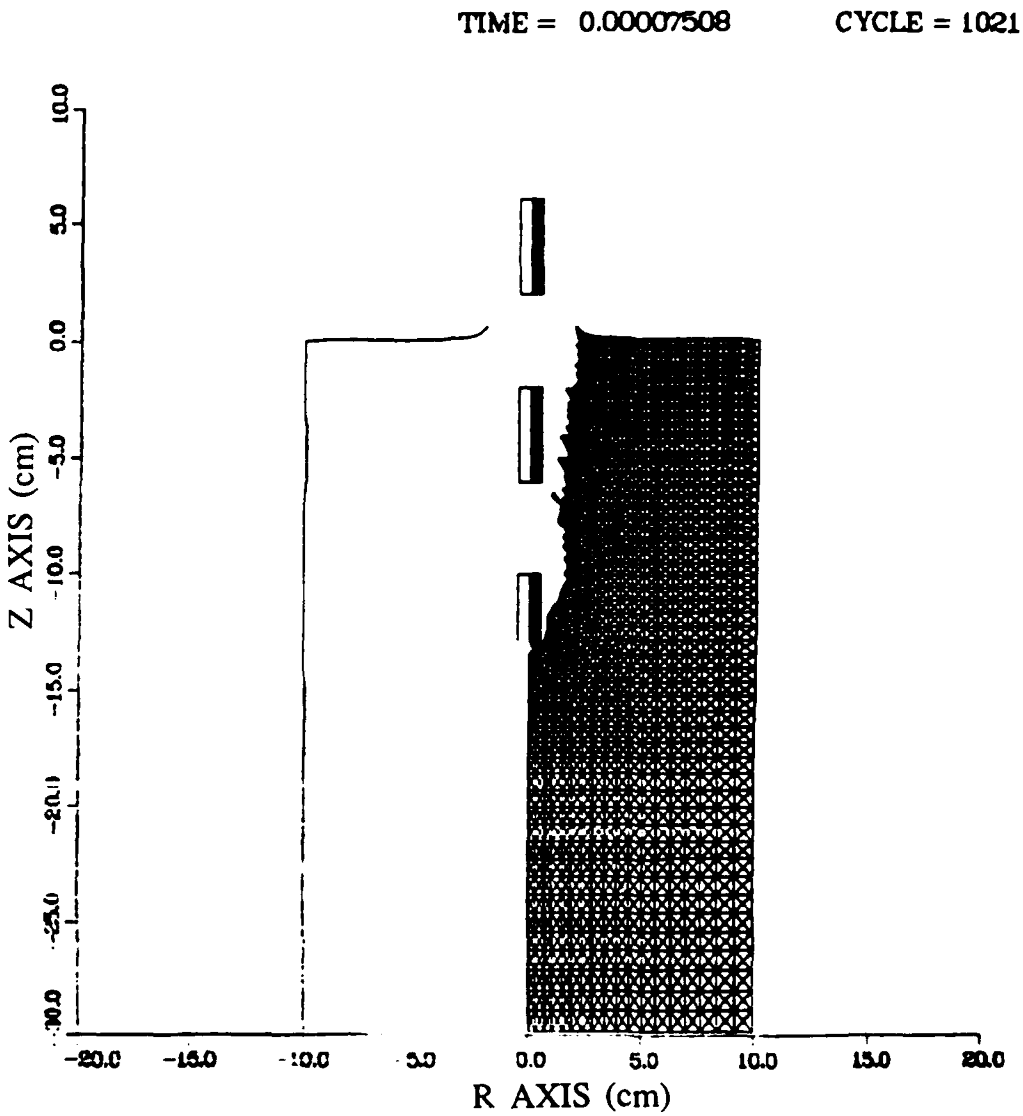

Figure 6. Computed Deformation of Segmented Rod and Target at 75 μs, V_s = 4 km/s.

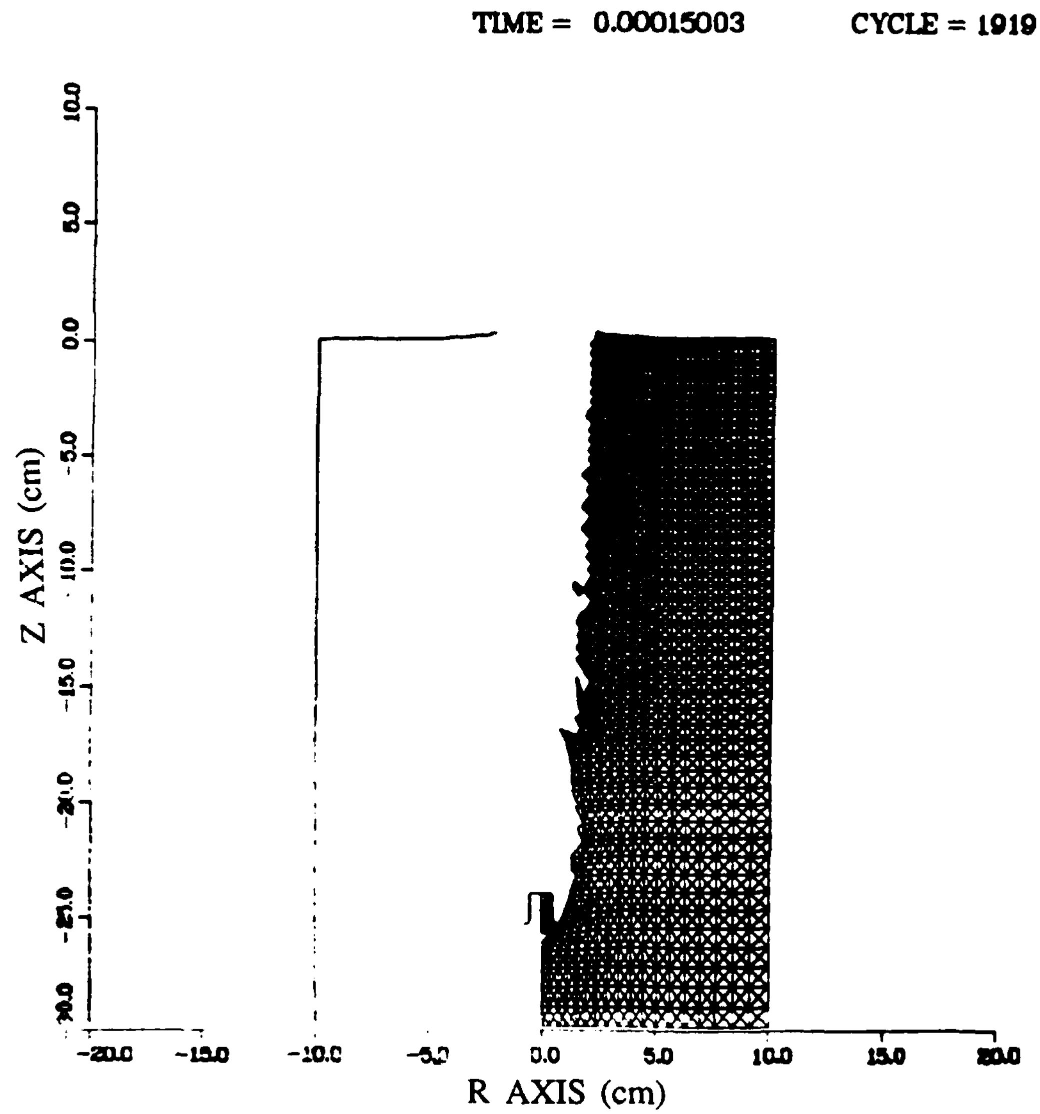

Figure 7. Computed Deformation of Segmented Rod and Target at 150 μs, V_s = 4 km/s.

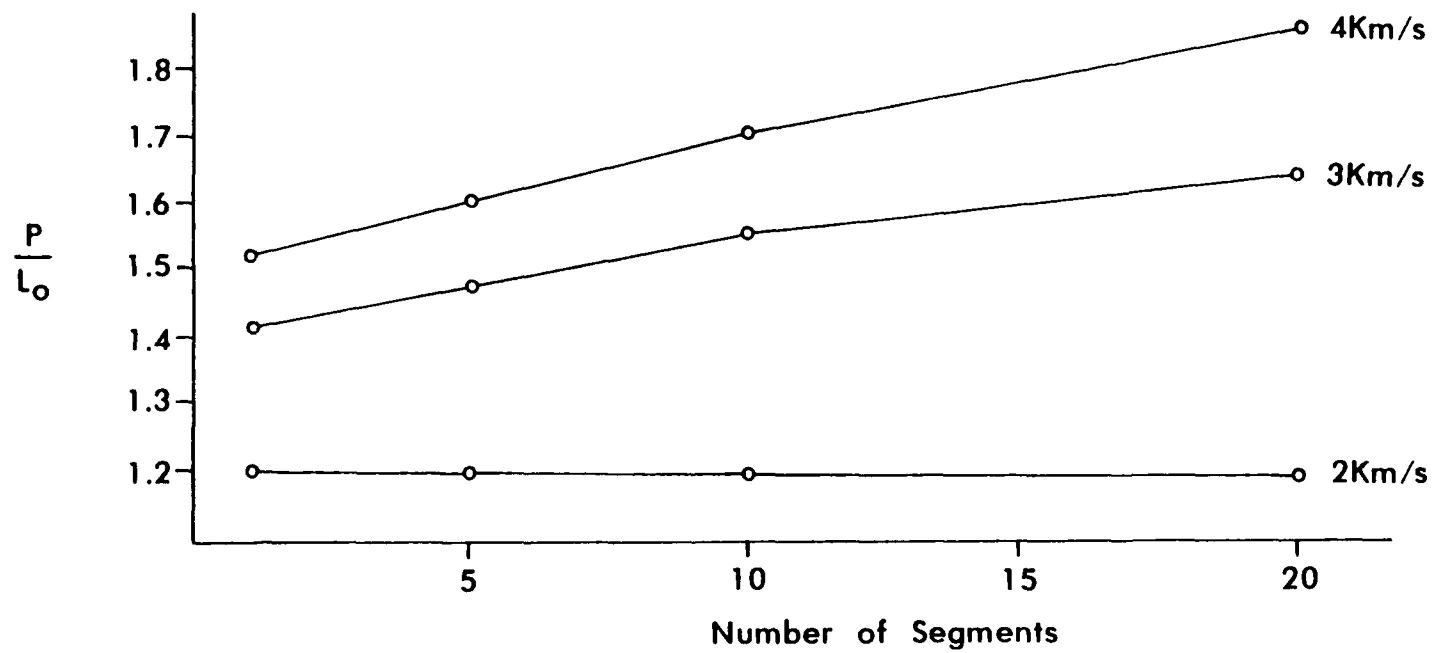

Figure 8. Effect of Segment Number on Penetration for S/D = 2.

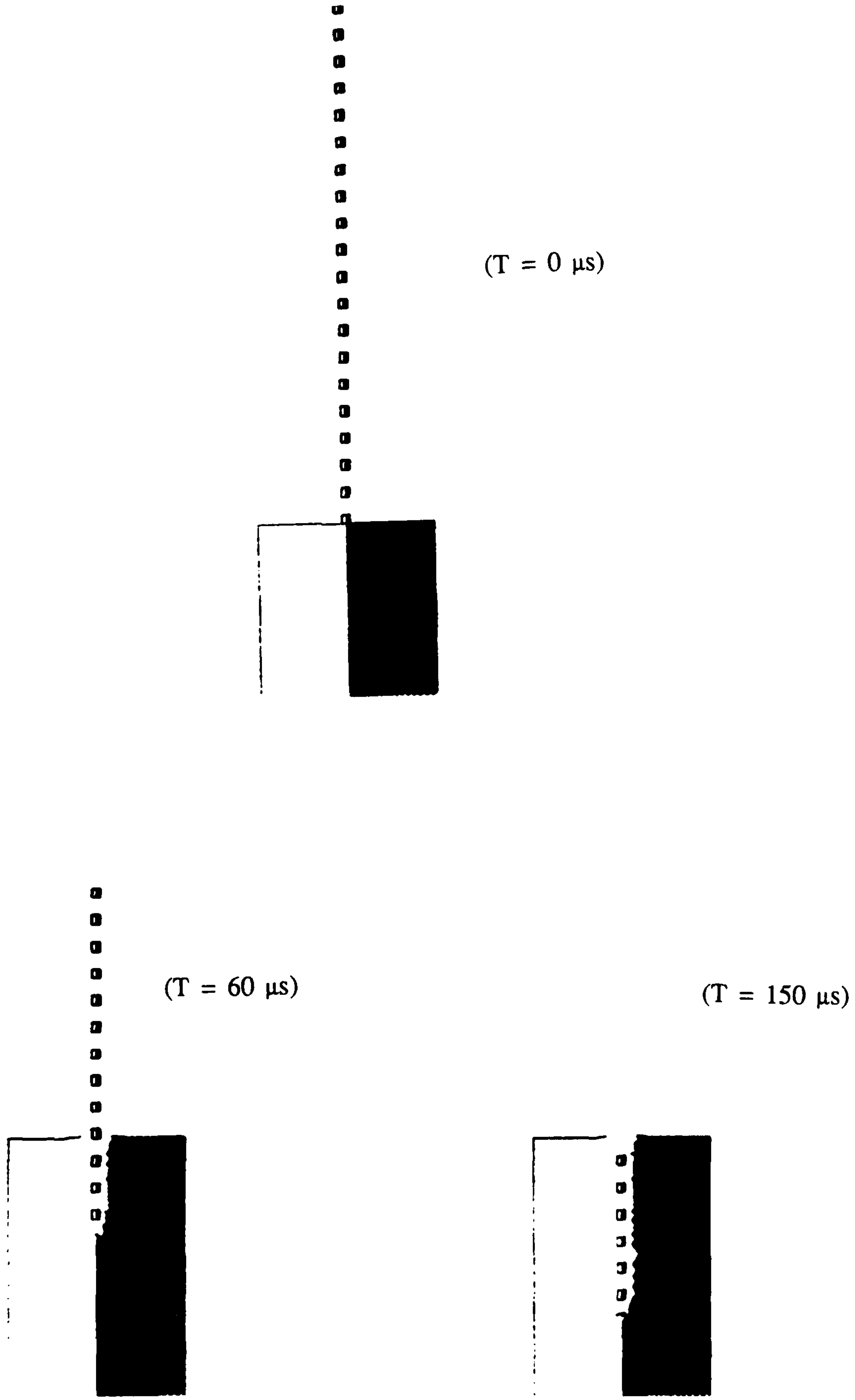

Figure 9. Impact of 20-Segment Rod at V_s = 4 km/s.

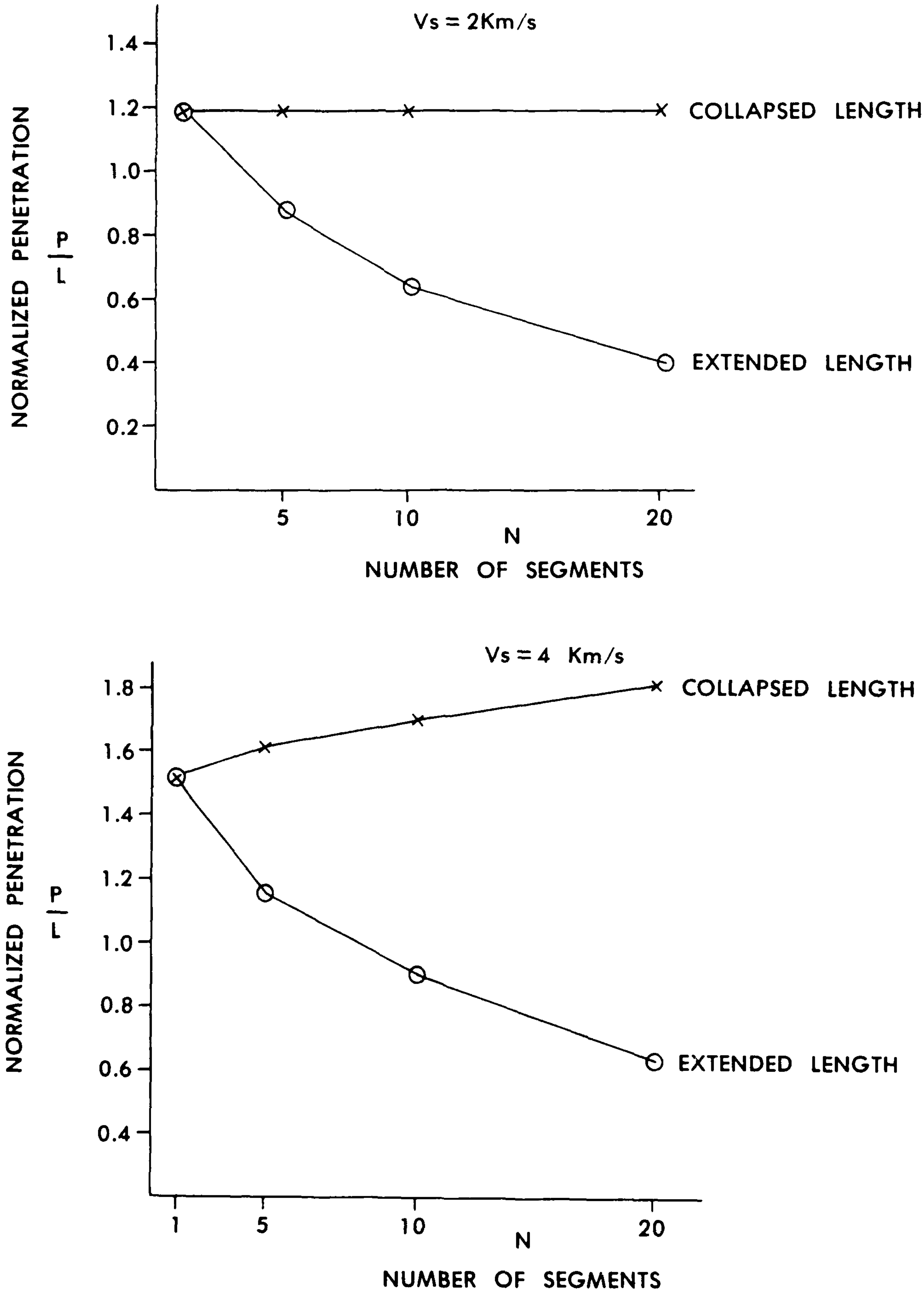

Figure 10. Penetration Normalized by Collapsed and Extended Projectile Lengths at Two Striking Velocities.

TABLE 1. Penetration Performance of Continuous and Segmented Rods.

Continuous

Vs km/s	P cm	P/L_o
1.5	19.2	0.92
2.0	24.0	1.20
3.0	28.2	1.41
4.0	30.4	1.52

Segmented

V_s km/s	S/D	P cm	P/L_o
1.5	1	18.0	0.90
	2	18.4	0.92
	4	19.4	0.98
2.0	1	22.0	1.10
	2	24.0	1.20
	4	24.0	1.20
3.0	1	29.6	1.48
	2	29.7	1.48
	4	30.2	1.51
4.0	1	32.0	1.60
	2	32.0	1.60
	4	33.3	1.67

L_o = length of continuous rod/collapsed length of segmented rod.

TABLE 2. Effect of Segmentation on Penetration.

V_s km/s	N	P cm	P/L_o
2	1	24.0	1.20
	5	24.0	1.20
	10	24.0	1.20
	20	24.0	1.20
3	1	28.2	1.41
	5	29.4	1.47
	10	30.4	1.52
	20	32.0	1.60
4	1	30.4	1.52
	5	32.2	1.61
	10	34.2	1.71
	20	36.5	1.82

N = number of segments (1 = continuous rod).

L_o = length of continuous rod/collapsed length of segmented rod.

TABLE 3. Comparison of Penetration Data With Different Normalizations.

V_s km/s	N	L_o cm	L cm	P cm	P/L_o	P/L
2	1	20	20	24	1.2	1.2
	5	20	28	24	1.2	0.86
	10	20	38	24	1.2	0.63
	20	20	58	24	1.2	0.41
3	1	20	20	28.2	1.41	1.41
	5	20	28	29.4	1.47	1.05
	10	20	38	30.4	1.52	0.80
	20	20	58	32	1.60	0.55
4	1	20	20	30.4	1.52	1.52
	5	20	28	32.2	1.61	1.15
	10	20	38	34.2	1.71	0.90
	20	20	58	36.5	1.82	0.63

L_o = length of continuous rod/collapsed length of segmented rod.

L = extended length of segmented rod.

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